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September 1, 1991

Dr. S. Lekoudis
Director, Mechanics Division
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217-5000

Title:	Dynamic Fracture Criterial in Structural Solids
ONR Control No.:	85-K-0596
ONR Work Unit No.:	4324745
Final Report:	October 1, 1988 - September 30, 1990
Scientific Officer:	Dr. Yapa Rajapakse

Dear Dr. Lekoudis:

This is a final report for contract/grant N00014-85-K-0596, which expired December 1, 1989. The program was concerned with the experimental, numerical and analytical study of elastic-plastic and dynamic fracture phenomena in metal alloys. Its goal was the detailed investigation of failure mechanisms in solids subjected to very high rates of loading and the subsequent establishment of accurate and useful crack initiation and dynamic crack growth criteria in such materials.

The experimental part of our program involved the development and use of new experimental techniques for the measurement of *highly transient* field quantities (e.g., displacements, strains or temperature fields) generated during the dynamic fracture process. Such diagnostic techniques include a variety of high resolution optical methods in the visible wavelength range, based on both coherent and incoherent optics which were used in conjunction with high speed photography. In the non-visible wavelength range we developed a high speed infrared sensor system that has been used for the measurement of highly transient temperature fields generated during dynamic fracture.

The numerical part of our program was concerned with the development of very elaborate finite element models designed to investigate dynamic fracture phenomena and to accurately include the effects of three dimensionality, rate sensitivity and material inertia in the analysis of the dynamic failure process. Our most recent interests in this area included the use of continuum damage theories that model the void nucleation and growth process at the vicinity of dynamic cracks. These models were used for the numerical investigation of processes related to crack tip tunneling in ductile metals as well as the formation of shear lips during crack growth.

The numerical computations were designed to simulate actual experimental arrangements and their results were *always* compared by means of the optical and thermographic methods developed in our laboratory.

Our accomplishments in the above areas is briefly described as follows:

A. DYNAMIC CRACK GROWTH IN HIGH STRENGTH METAL ALLOYS

Development of a new experimental arrangement for the investigation of the domain of dominance of asymptotic fields in dynamic fracture (Bifocal Caustics).

The question of the domain of dominance of the asymptotic elastic fields in dynamic fracture is addressed for the two cases of a dynamically loaded stationary crack as well as a dynamically propagating crack. The experiments reported in this work are conducted on 4340 steel, 3-point bend specimens loaded dynamically using a drop-weight tower. A new optical configuration - the method of bifocal caustics - is used in conjunction with high speed photography, to measure the apparent stress-intensity factor simultaneously from two different regions (initial-curves) around the crack-tip. If the initial-curves lie within the domain of dominance of the asymptotic field, the measured values of the dynamic stress-intensity factor must be the same. By suitably adjusting the optical set-up, a range of initial-curves are scanned in an attempt to map the domain from which the dynamic stress-intensity factor can be experimentally obtained.

Concurrently, instrumented impact hammer and supports are used to monitor the dynamic boundary conditions that the specimens are subject to. These boundary conditions are then used in a dynamic, three-dimensional finite-element simulation of the experiments. A domain integral approach is used to numerically extract the stress-intensity factor values. Comparison of the numerical results with the experiments is then made in an effort to identify the effects of three-dimensionality and transient conditions on the measured stress-intensity factor values. The main conclusion of this work is the following: During transient crack growth, the domain of dominance of the asymptotic elasto-dynamic solution may shrink to zero, creating serious problems in the interpretation of experimental data. In particular the classical analysis of optical caustics may result in errors in excess of 50% in value of the dynamic stress intensity factor. Our progress has been documented in references [A.1, A.13, A.14] of enclosure (2).

B. 3-D CRACK TIP FIELDS IN DUCTILE FRACTURE

The numerical analysis

A simultaneous numerical and experimental investigation was undertaken to assess three-dimensional effects and HRR dominance near a crack front in a ductile 3-point bend specimen. In parallel to the 3-D numerical calculations, a plane-strain and a plane-stress analysis of the same in-plane specimen geometry was performed to obtain upper and lower bounds for the 3-D calculation. The radial, angular and thickness variation of the stresses and displacements were studied in great detail from contained yielding, to fully plastic conditions. The results indicate that the plane strain HRR field prevails in the interior of the specimen very near the crack front even for moderate extents of yielding. On the other hand, for distances from the crack tip exceeding about half a specimen thickness, plane stress conditions are approximated. (For details see reference [A.6, A.9].)

Experiments and the dynamic measurement of J

The calculations discussed above modeled a series of laboratory experiments involving three independent experimental techniques. The experiments examine the possibility of using the optical method of caustics for the measurement of the J integral in the presence of large scale yielding and three dimensional fields is also investigated. Experiments using the optical method of caustics by reflection and Twyman-Green interferometry were performed simultaneously on either side of the test specimen. The load and load-point displacement were also measured. The experimental results were compared with very good agreement to the results of the finite element simulation of experiment, described above. The caustics experiments were used to obtain a calibration relation between the value of the J integral and the caustic diameter, D, for load levels up to fracture initiation. It was proposed that such a calibration be used in dynamic fracture initiation experiments for the measurement of the time history of the dynamic J integral. (For details see reference [A.2., A.5, A.10].)

To test the proposed technique, specimens of the same geometry as in the static experiments were loaded dynamically in impact. The resulting caustic patterns, recorded using high speed photography, were analyzed on the basis of the J vs. D calibration relation to determine the time history of J^d. Final verification of the procedure was provided by comparing the history of $J^d(t)$ from caustics to an independent determination of $J^d(t)$ based on a dynamic elastic-plastic finite element analysis. The numerical simulation, which used the experimentally measured loads as traction boundary conditions showed very good agreement with experiment. (See reference [A.11, A.12].)

C. STUDY OF DYNAMIC FAILURE MODES IN METALS: TEMPERATURE MEASUREMENTS APPLIED TO THE INVESTIGATION OF THE ROLE OF SHEAR LIP FORMATION ON DYNAMIC FRACTURE TOUGHNESS.

Postmortem experimental observations of dynamic fracture surfaces in moderately ductile metal plates reveal that the failure mode in the interior of the metal plate differs drastically from that observed near the specimen free surface. In particular, it is observed that dynamic cracks generally tend to propagate in a flat manner in the plate interior, while near the specimen surface they propagate through the formation of two 45^o shear-bands which form a three-dimensional structure often referred to as the "shear lip". (See reference [A.19].) The ratio of the width of the shear lip over the plate thickness depends on the material properties, and for the case of dynamic crack growth it often is (for highly rate sensitive metals) a strong function of crack propagation velocity.

The goal of this investigation was two-fold. First, we were interested in studying the role of shear lip formation as a toughening mechanism in structural steels. More specifically we attempted to estimate the percentage of total fracture energy dissipated in the formation of shear lips during dynamic ductile crack growth at different crack propagation speeds. Second, we were interested in assessing the effect of the competing mechanisms of strain rate hardening and thermal softening on the selection of failure modes during dynamic fracture.

Our experimental arrangement made use of a linear array of high speed infrared temperature sensors to record the amplitude and spatial structure of the transient temperature fields at the vicinity of dynamically propagating cracks in metals. This high resolution measurement was performed in real time on the specimen surface and revealed the three dimensional structure of the failure propagation mechanism there. The maximum temperatures recorded were in excess of $600^o C$ while the measured temperature profiles clearly indicated the mechanism of dynamic shear lip formation which proceeds through the formation of dynamic shear bands intersecting the free surface of the specimen at $\pm 45^o$.

The measured temperature profiles were also used to calculate the plastic work rate density on the specimen surface and to thus estimate the amount of energy dissipated through the formation of shear-lips at different crack tip speeds. This estimate was compared to the total fracture energy available for crack growth and an energy balance is thus attempted.

Our preliminary results indicated that at crack velocities of the order of 0.3 of the shear wave speed, as much as 70% of the energy available to the crack through far field loading is dissipated in the dynamic formation of shear lips while only 30% is left for the propagation of the flat fracture in the specimen interior. The consequences of this result were far reaching given the small thickness of the shear lips observed in the heat-treatment of the 4340 steel tested. The measurements clearly showed that the formation of shear lips has a substantial effect on the elevation of crack growth resistance in plate specimens of even moderately ductile metals. The main results on this investigation were reported in references [A.15, A.16].

D. DEVELOPMENT OF A NEW OPTICAL TECHNIQUE FOR DYNAMIC FRACTURE STUDIES: THE COHERENT GRADIENT SENSOR METHOD (C.G.S.)

Our earlier investigations under our ONR grant have concentrated on the issue of the reliability of optical techniques in measuring fracture parameters in dynamic fracture mechanics. Many investigators have used the assumption of K_I^d-dominance in their experimental study of fundamental issues such as the dependence of the dynamic fracture toughness on crack tip velocity, acceleration, temperature, etc. Based on experimental results obtained from techniques such as photoelasticity and caustics, these investigators have debated the existence of a unique relation between dynamic fracture toughness and crack tip speed.

In our earlier work (see section A of this report) we addressed the following questions: Is the assumption of K_I^d-dominance valid in commonly used laboratory specimens subjected to highly transient loading conditions? If not, what are the errors introduced in the interpretation of optical patterns? And finally: Do these errors account for the controversy regarding the uniqueness of the K_{Ic}^d vs. $\dot{a}$ (speed) relation?

Our dynamic experiments using the method of caustics in a bifocal arrangement (see refs. [3,5,6,7,8,9]) have directly demonstrated that this technique may result in substantial errors if interpreted on the basis of the existence of an asymptotic K_I^d field on commonly used specimen configurations where such a field may never be established because of three dimensional or transient effects. (See sections A and B of this report.)

Our most recent efforts have concentrated towards the development of new optical experimental techniques which will provide a better alternative to caustics in the sense that their interpretation would not depend on the restrictive assumption of K_I^d-dominance. To that effect we have been successful in developing a new full field optical method which we named the Coherent Gradient Sensor (C.G.S.), which shows great promise in the study of deformation fields at the vicinity of crack tip in both opaque and transparent solids. This technique is capable of measuring in-plane gradients of out-of-plane displacements $\frac{\partial u_3}{\partial x_1}, \frac{\partial u_3}{\partial x_2}$ in *opaque* solids. Figure 1 shows a C.G.S. fringe pattern obtained by reflection from the surface of a cracked metal specimen. The technique is also applicable to *transparent* materials where it records in-plane gradients of stress fields, $\frac{\partial}{\partial x_1}(\sigma_{11}+\sigma_{22}), \frac{\partial}{\partial x_2}(\sigma_{11}+\sigma_{22})$.

This method exhibits the following advantages for the dynamic fracture testing of materials. Unlike photoelasticity, it can be applied to both transparent and opaque solids, and for transparent materials it does *not* hinge on the requirement of birefringence. In addition, it is sensitive to gradients of displacements or stress fields, and in this sense it provides a **full field, coherent analogue** to the optical method of transmitted or reflected caustics, which are also sensitive to gradients of stress or out-of-plane displacement. However, unlike caustics, C.G.S. provides full field information near the crack, whose interpretation does not depend on the assumption of K_I^d-dominance. As a full field technique, it can be used to study both dynamic crack growth as well as other dynamic failure processes such as adiabatic shearbanding. This is not true for caustics whose interpretation requires detailed *apriori* knowledge of the structure of deformation fields which is completely unavailable for dynamic shearbands. Yet the most impressive feature of C.G.S. is its potential use in conjunction with high speed photography. Unlike other interferometric methods, C.G.S. does *not* suffer from severe light limitations and is thus an excellent candidate for high speed photography where very short exposure times (10 ns) forbid the efficient use of other full field interferometric methods.

Our continuing work has concentrated on the complete study of the accuracy of this new technique for quasistatic and dynamic fracture situations. Our progress to date is documented in ref. [A.17, A.18].

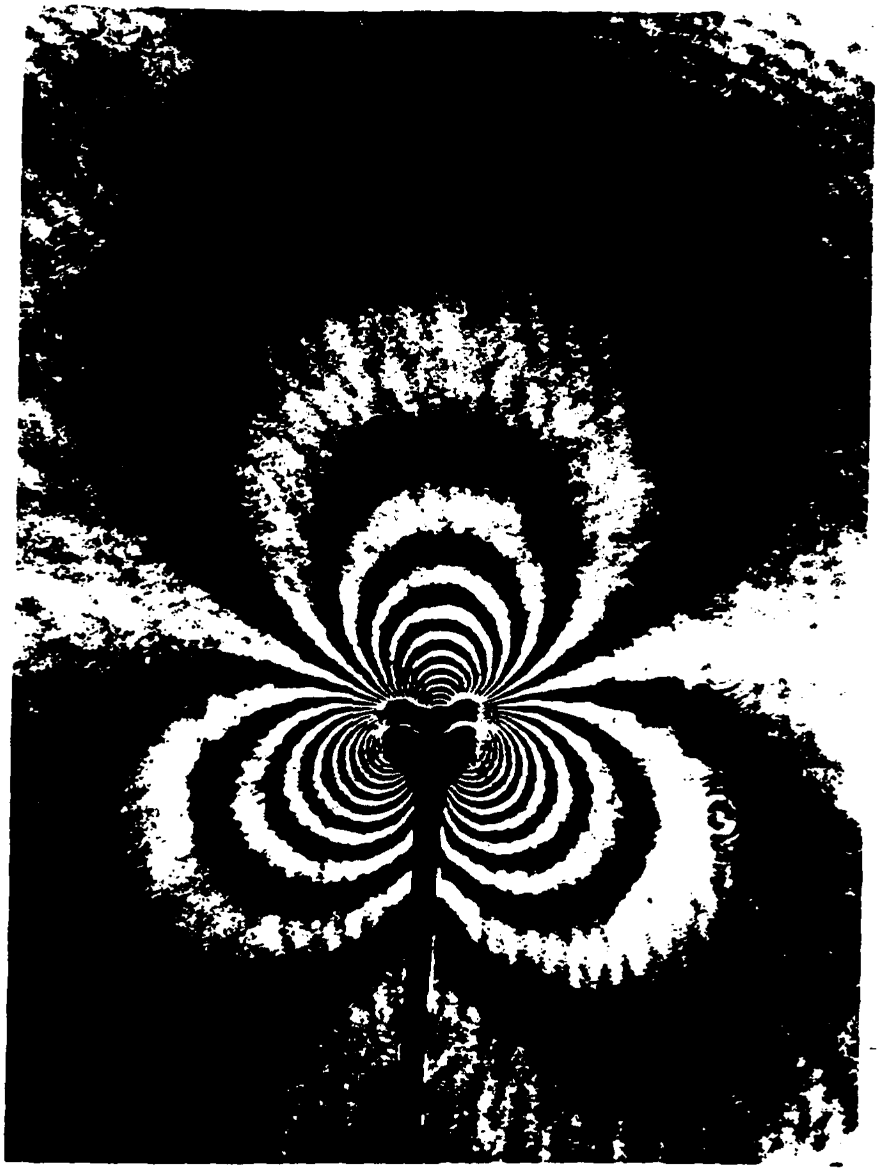

Figure 1 - Full field optical pattern obtained by means of the newly developed Coherent Gradient Sensor technique (Caltech 1989). Fringes corresponding to contours of equal $\frac{\partial u_2}{\partial x_1}$. This technique is the full field equivalent of caustics by reflection.

Our future plans include the application of the new technique to dynamic fracture mechanics. Our preliminary results in this direction are already very encouraging. We are interested in developing this technique as an alternative over the method of reflected caustics for the study of the dynamic failure of metals. We expect that a full field technique like C.G.S. will provide the means of completely understanding the sources of experimental error that have been responsible for recent controversies in our subject. To this effect, we wish to resolve the question of the uniqueness of the K_{Ic}^d vs. $\dot{a}$ relationship once and for all, for both opaque and transparent materials.

E. NUMERICAL STUDIES OF ELASTIC-PLASTIC DYNAMIC CRACK GROWTH IN METALS.

We have completed a series of very detailed numerical investigations whose goal is the precision modeling of dynamic elasto-plastic crack growth under *plane stress* conditions. The first part of this work considers the case of a plane stress crack propagating at different crack tip velocities, $\dot{a}$ (from 0.0 to 0.5 the material shear wave speed), under conditions of small scale yielding. The detailed finite element model (smallest element equals 1/15,000 of the plastic zone size) first serves to examine the effect of inertia on the near tip stress and strain distribution. We study the asymptotic nature of these field quantities, deeply within the propagating active plastic zone and examine their dependence on crack tip velocity. It should be emphasized here that although asymptotic analytical solutions are available for plane strain and anti-plane shear dynamic crack growth, the plane stress case has been illusive. Our goal is to provide extensive detailed numerical information of the radial and circumferential structure of the near tip deformation fields and to thus guide theoretical development on this subject. [A.3, A.6, A.7, A.8, A.20, A.21]

The second part of this investigation is related to our experimental studies of dynamic crack growth in thin metal plates as follows: We consider a local (near-tip) ductile fracture propagation criterion which states that the crack will propagate dynamically if at a certain microstructural distance from the crack tip the equivalent plastic strain will reach a critical value which is material dependent. By imposing this criterion and using the results of our small scale yielding finite element calculation, we obtain a theoretical relation between the far field dynamic stress intensity factor and the crack tip velocity. This relation is successfully compared to our experimental measurements performed on thin 4340 steel plates by means of optical techniques and high speed photography. See references [A.22, A.24].

Our most recent accomplishments in this area include the detailed numerical study of crack growth under conditions which are not strictly "small scale yielding". Here we are intereste' in modeling dynamic crack growth in laboratory specimens where the assumption of the existence of a purely K_I-dominant zone surrounding the plastic zone is no longer applicable. For details see reference [A.23]. This related to the issues of teh existence of a unique K_{Ic}^{d} vs. $\dot{a}$ relationship already discussed in sections A and D. Our plans call for the direct comparison of experimental results obtained by means of the newly developed optical technique (C.G.S.) and our numerical investigation.

Sincerely,

Ares J. Rosakis

Ares J. Rosakis
Associate Professor of Aeronautics
and Applied Mechanics

AJR:kcm

Enclosures

PARTICIPANTS IN RESEARCH (ENCLOSURE (1))

A. Zehnder	Formerly a graduate student and subsequently Research Fellow in Aeronautics, Caltech.
R. Narasimhan	Formerly a graduate student and subsequently Research Fellow in Applied Mechanics, Caltech.
S. Krishnaswamy	Formerly a graduate student and subsequently Research Fellow in Aeronautics, Caltech.
H. Tippur	Formerly a Research Fellow in Aeronautics, Caltech.
X. Deng	Graduate Research Assistant in Applied Mechanics, Caltech.

CURRENT AFFILIATIONS OF RESEARCH PARTICIPANTS

All of the above mentioned researchers currently hold *academic positions* in American and foreign universities. Dr. Zehnder is an Assistant Professor of Applied Mechanics at Cornell University, Dr. Narasimhan is an Associate Professor of Applied Mechanics at the Indian Institute of Science in Bangalore, India. Dr. Krishnaswamy is an Assistant Professor of Civil Engineering at Northwestern University. Dr. Tippur is an Assistant Professor of Mechanical Engineering at Auburn University while Dr. Deng is an Assistant Professor of Mechanical Engineering at the University of South Carolina.

CURRENT GRANTS AND CONTRACTS

1. Dynamic Fracture Modes in Metal Alloys
   ONR Contract Number N00014-90-J-1340
   Scientific Officer: Dr. Y. Rajapakse
   Amount: 465,067

2. Dynamic Fracture of Bimaterial Interfaces
   NSF Contract Number: 4-MSS-9024838
   Scientific Officer: Dr. Lallit Anand
   Amount: 218,588

LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS (ENCLOSURE (2))

A. PAPERS PUBLISHED IN REFEREED JOURNALS

1. Rosakis, A.J. and Zehnder, A.T.,
"On the Dynamic Fracture of Structural Metals." *International Journal of Fracture,* Special Issue on Dynamic Fracture, M.L. Williams and W.G. Knauss (Eds), Martinus Nijhoff Publishers (1985), pp. 43-60.

2. Zehnder, A.T. and Rosakis, A.J.,
"A Note on the Measurement of K and J under Small Scale Yielding Conditions Using the Method of Caustics," *International Journal of Fracture,* Vol. 30 (1986), R43-R48. (First published as a Caltech Report prepared for the National Science Foundation, SM 85-18.)

3. Narasimhan, R. and Rosakis, A.J.,
"Reexamination of Jumps Across Quasistatically Propagating Surfaces Under Generalized Plane Stress in Anisotropically Hardening Elastic-Plastic Solids," *Journal of Applied Mechanics,* Vol. 54 (1987), pp. 519-524. (First published as a Caltech Report prepared for the Office of Naval Research, SM 86-3.)

4. Zehnder, A.T. and Rosakis, A.J.,
"Dynamic Fracture Initiation and Propagation in 4340 Steel Under Impact Loading," *International Journal of Fracture, (1988).* (First published as a Caltech Report prepared for the Office of Naval Research, SM 86-6.)

5. Zehnder, A.T., Rosakis, A.J., and Narasimhan, R.,
"Measurement of the J. Integral with Caustics: An Experimental and Numerical Investigation," to appear in *ASTM-STP (1988) Special Volume on Non-linear Fracture Mechanics.* (First published as a Caltech Report prepared for the Office of Naval Research and NSF, SM 86-8.)

6. Narasimhan, R. and Rosakis, A.J.,
"Numerical Study of Stationary Plane Stress Cracks in Elastic-Plastic, Power Hardening Solids," *Journal of the Mechanics and Physics of Solids,* Vol. 36 (1988), pp. 77-117. (First published as a Caltech Report prepared for the Office of Naval Research and the National Science Foundation, SM 86-21.)

7. Narasimhan, R., Rosakis, A.J., and Hall, J.,
"A Finite Element Study of Stable Crack Growth Under Plane Stress Conditions; Part I: Elastic-Prefectly Plastic Solids." *Journal of Applied Mechanics, Vol. 54 (1987), pp. 838-845.* (First published as a Caltech Report prepared for the Office of Naval Research, SM 86-22.)

8. Narasimhan, R. and Rosakis, A.J., and Hall, J.,
"A Finite Element Study of Stable Crack Growth Under Plane Stress Conditions; Part II: Influence of Hardening." *Journal of Applied Mechanics,* Vol. 54 (1987), pp. 845-853. (First published as a Caltech Report prepared for the Office of Naval Research, SM 86-23.)

9. Narasimhan, R., and Rosakis, A.J.,
"Three Dimensional Effects near a Crack Tip in a Ductile Three Point Bend Specimen, Part I: Numerical Investigations." To appear in *Journal of Applied Mechanics,* January, 1990. (First published as a Caltech Report, SM 88-6.)

10. Zehnder, A.T. and Rosakis, A.J.,
"Three Dimensional Effects near a Crack Tip in Ductile Three Point Bend Specimen, Part II: An Experimental Investigation, using Interferometry and Caustics." To appear in the *Journal of Applied Mechanics,* January 1990. (First published as a Caltech Report, SM 88-7.)

11. Zehnder, A.T., Rosakis, A.J. and Krishnaswamy, S.,
"Dynamic Measurement of the J-Integral in Ductile Metals: Comparison of Experimental and Numerical Techniques." *International Journal of Fracture,* Special Issue on Non-linear Fracture Mechanics, edited by W.G. Knauss and A.J. Rosakis, Vol. 42, 1990. Also, Proceedings of the IUTAM symposium on Recent Advances on Non-linear Fracture Mechanics, Caltech, March 14-16, 1988.

12. Rosakis, A.J., Zehnder, A.T. and Narasimhan, R.,
"Caustics by Reflection and their Application to Dynamic and Elastic- Plastic Fracture Mechanics", *Journal of Optics and Laser Engineering,* Vol. 27, No. 8, pp. 596-610.

13. Krishnaswamy, S., and Rosakis, A.J.
"On the Extent of Dominance of Asymptotic Elastodynamic Crack-Tip Fields ; Part I: An Experimental Study Using Bifocal Caustics". To appear in the *Journal of Applied Mechanics, 1990.* (First published as a Caltech Report, SM 88-21.)

14. Krishnaswamy, S., Rosakis, A.J., and Ravichandran, G.
"On the Extent of Dominance of Asymptotic Elastodynamic Crack-Tip Fields; Part II: A Numerical Investigation of Three-Dimensional and Transient Effects". To appear in the *Journal of Applied Mechanics,* 1990. (First published as a Caltech Report, SM 88-22.)

15. Zehnder, A.T., and Rosakis, A.J.
"A Note on High Resolution Infrared Measurements of Temperature Fields Generated During Dynamic Crack Growth in Metals". To appear as a "Brief Note" to the *Journal of Applied Mechanics,* 1990.

16. Zehnder, A.T. and Rosakis, A.J.
"On the Temperature Distribution at the Vicinity of Dynamically Propagating Cracks in 4340 Steel: High Resolution Measurements by Means of High Speed Infrared Sensors." To appear in the *Journal of the Mechanics and Physics of Solids,* 1990. (First published as a Caltech Report, SM 89-2.)

17. Tippur, H.V., Krishnaswamy, S. and Rosakis, A.J.
"A Coherent Gradient Sensor for Crack Tip Deformation Measurements: Analysis and Experimental Results." To appear in the *International Journal of Fracture,* 1990. (First published as a Caltech Report, SM 89-3.)

18. Tippur, H. V., Krishnaswamy, S., and Rosakis, A. J.,
"Optical Mapping of Crack Tip Deformations Using the Method of Transmission and Reflection Coherent gradient Sensing: A Study of Crack-tip K-Dominance" Caltech Report AM89-11, 1989, to appear in the *International Journal of Fracture,* 1990.

19. Narasimhan, R., Rosakis, A.J. and Moran, B.
"A Three Dimensional Numerical Investigation of Fracture Initiation by Ductile Failure Mechanisms in 4340 Steel," Caltech Report SM89-5, to appear in the *International Journal of Fracture*, 1990.

20. Deng, X. and Rosakis, A.J.
"Negative Plastic Flow and Its Prevention in Elasto-Plastic Finite Element Computation," GALCIT Report SM90-10; in *Finite Elements in Analysis and Design*, Vol. 7, pp. 181-191, 1990.

21. Deng, X. and Rosakis, A.J.
"Dynamic Crack Propagation in Elastic-Perfectly Plastic Solid Under Plane Stress Conditions," GALCIT Report SM90-11, Caltech; to appear in *Journal of the Mechanics and Physics of Solids*, 1990.

22. Deng, X. and Rosakis, A.J.
"A Finite Element Investigation of Quasi-Static and Dynamic Asymptotic Crack Tip Fields in Hardening Elastic-Plastic Solids Under Plane Stress; Part I: Crack Growth in Linear Hardening Materials," GALCIT Report SM90-12, Caltech; to appear in the *International Journal of Fracture*, June, 1990.

23. Deng, X., Rosakis, A.J. and Krishnaswamy, S.
"Dynamic Crack Propagation in Elastic-Plastic Solids Under Non-K-Dominance Conditions," GALCIT Report SM90-14, Caltech; submitted to the *International Journal of Solids and Structures* December, 1990.

24. Deng, X. and Rosakis, A.J.
"Energy Dissipation and Temperature Rise Near a Propagating Crack Tip in an Elastic-Plastic Solid," in preparation August, 1990.

B. ALL OF THE ABOVE WERE INITIALLY PREPARED AS TECHNICAL REPORTS FOR ONR.

C. PUBLICATIONS IN CONFERENCE PROCEEDINGS, CONFERENCE PRESENTATIONS, AND REPORTS:

Invited

1. Rosakis, A.J. and Zehnder, A.T.,
Dynamic Initiation and Unstable Growth of Cracks in Metals Under Impact Loading Conditions," *Special Session on Dynamic Fracture*, 23rd Annual Meeting of the Society of Engineering Science, Buffalo, NY, August 1986. (Invited Contribution)

2. Narasimhan, R. and Rosakis, A.J.,
"Influence of Hardening on the Quasi-static Extension of Mode-I Plane-Stress Cracks in Isotropic Elastic-Plastic Materials," *Proceedings of the International Conference on Fracture and Fracture Mechanics (ICFFM)*, Shanghai, China, April 1987. (Invited Contribution)

3. Rosakis, A.J.,
"Plane Stress Crack Initiation and Growth in Elastic Plastic Solids: A Numerical and Experimental Study," ASME Summer Annual Meeting, Cincinnati, Ohio, June 1987. (Invited Contribution)

4. Rosakis, A.J.,
"Experimental Aspects of Dynamic Fracture Mechanics," Prepared for the Fall Conference of the Society of Experimental Mechanics (S.E.M.), devoted to "Dynamic Failure", Savannah, Georgia, Oct. 1987 (Invited contribution)

5. Rosakis, A.J.,
"On the Application of Optical Caustics to the Investigation of Dynamic Fracture Mechanics Problems." *Focused Lecture Series on Instrumentation and Measurement at High Strain Rates*, UCSD, La Jolla, California, March 1988. (Invited Contribution)

6. Rosakis, A.J.,
"On Dynamic Failure Mechanics," *Fourth International Conference on Mechanical Properties of Materials at High Rates of Strain*, Oxford, England, March 20-22, 1989. (Invited Contribution.)

7. Zehnder, A.T., and Rosakis, A.J.,
"Dynamic Measurement of the J Integral in Ductile Metals, Using the Optical Method of Caustics," *12th Canadian Congress of Applied Mechanics*, (CANCAM), Ottawa, Canada, 28 May-2 June, 1989. (Invited Contribution.)

8. Rosakis, A.J., and Zehnder, A.T.,
"High Resolution, Infrared Measurements of Temperature Fields Generated During Dynamic Crack Growth in Metals," *The Oji International Seminar on Dynamic Fracture*, Toyohashi, Japan, August 1-4, 1989. (Invited Contribution.)

Contributed

1. Narasimhan, R., Rosakis, A.J., and Hall, J.,
"A Finite Element Study of Stable Crack Growth Under Plane Stress Conditions in Elastic-Plastic Solids," 10th U.S. National Congress in Applied Mechanics, Austin, TX, June 1986.

2. Zehnder, A.T. and Rosakis, A.J.
"Basic Experiments on the Dynamic Fracture Initiation and Unstable Growth of Cracks in Metals Using Reflected Shadowgraphy," 10th U.S. National Congress in Applied Mechanics, Austin, TX, June 1986.

3. Zehnder, A.T., Rosakis, A.J., and Narasimhan, R.,
"Measurement of the J Integral with Caustics: An Experimental and Numerical Investigation," Third International Symposium on Nonlinear Fracture Mechanics," Knoxville, Tennessee, October 1986.

4. Narasimhan, R., and Rosakis, A.J.,
"Stable Crack Growth in Elastic-Plastic Solids Under Plane Stress Conditions: A Finite Element Study," *Proceedings of the 4th International Conference on Numerical Methods in Fracture Mechanics*, San Antonio, Texas, March 1987.

5. Rosakis, A.J., Zehnder A.T., and Narasimhan, R.,
"Caustics by Reflection and their Application to Dynamic and Elastic-Plastic Fracture Mechanics," to appear in the *Proceedings of the International Conference on Photomechanics and*

Spectrum Mechanics, San Diego, California, August 1987. (Invited Contribution),(First published as a Caltech Report prepared for the Office of Naval Research and the National Science Foundation, SM 87-17).

6. Rosakis, P.J. and Rosakis, A.J.,
"Aspects of Finite Deformation in Dislocation Problems," *Proceedings of the 20th Midwestern Mechanics Conference,* West Lafayette, Indiana, August 1987.

7. Krishnaswamy, S. and Rosakis, A.J.,
"Viscoplastic Analysis of Dynamic Growth Under Mode-I, Plane-Stress Conditions," 24th Annual Technical Meeting of the Society of Engineering Science, Salt Lake City, Utah, September 1987.

8. Rosakis, A.J., Zehnder, A.T., and Narasimhan, R.,
"Dynamic Measurement of the J Integral by the Optical Method of Caustics," *Proceedings of the Fall Conference of the Society of Experimental Mechanics* (SEM), *devoted to "Dynamic Failure",* Savannah, Georgia, October 1987. (First published as a Caltech Report prepared for the Office of Naval Research, SM 87-22).

9. Narasimhan, R., Rosakis, A.J. and Hall, J.,
"A Finite Element Study of Stable Crack Growth Under Plane Stress Conditions in Elastic-Plastic Solids. Part I: Elastic-Perfectly Plastic Solids, Part II: Influence of Hardening.", Presented at the A.S.M.E. Winter annual meeting. Boston, Massachusetts, December, 1987.

10. Narasimhan, R., Zehnder, A.T., and Rosakis, A.J.,
"Three Dimensional Fields for a Through Crack in an Elastic-Plastic Solid: Numerical Analysis and Comparison to Interferometric Measurements". In the Proceedings of the *Symposium on Analytical, Numerical and Experimental Aspects of Three Dimensional Fracture Processes,* Edited by A.J. Rosakis, K. Ravichandar and Y. Rajapakse, Summer Annual Meeting of ASME, Berkeley, California, June, 1988.

11. Krishnaswamy, S., Rosakis, A.J. and Ravichandran, G.,
"A Bifocal Arrangement for Reflected Caustics for the Investigation of the Domain of Dominance of Asymptotic Elastic Fields in Dynamic Fracture," to appear in the Proceedings of the 7th International Conference on Fracture, Houston, TX., March (1989).

12. Krishnaswamy, S., Rosakis, A.J. and Ravichandran, G.,
"On the Domain of Dominance of Asymptotic Crack Tip Fields in the Dynamic Fracture of Metals: An Investigation Based on Bifocal Caustics and Three-Dimensional Dynamic Numerical Simulations," *2nd National Congress on Mechanics,* Athens, Greece, June 1989.

13. Krishnaswamy, S., Rosakis, A.J. and Ravichandran, G.,
"A Bifocal Arrangement for Reflected Caustics for the Investigation of the Domain of Dominance of Asymptotic Elastic Fields in Dynamic Fracture," *Proceedings of the International Pressure and Piping Conference,* July 23-27, 1989, Honolulu, Hawaii.

14. Zehnder, A.T. and Rosakis, A.J.,
"Experimental Measurement of Temperature Rise Generated During Dynamic Crack Growth in Metals," *Symposium on Experimental Techniques in Micromechanics,* ASME, WAM, San Francisco, December 1989.

15. Deng, X., and Rosakis, A.J.,
"Dynamic Elastic-Plastic Crack Propagation in Plane Stress", *26th Annual Meeting of the Society of Engineering Science*, University of Michigan, September 18-20, 1989.

16. Deng, X., and Rosakis, A.J.,
"Negative Plastic Flow and its Prevention in Elasto-Plastic Finite Element Computation", *Symposium on the Finite Element Method,* Duke University, March 1990.

17. Krishnaswamy, S., Tippur, V. and Rosakis, A.J.,
"Measurement of Dynamic Crack Tip Deformation Fields Using the Method of Coherent Gradient Sensing", *U.S. National Congress of Applied Mechanics,* University of Arizona, May, 1990.

18. "Narasimhan, R., Rosakis, A.J. and Moran, B.,
"A Three Dimensional Numerical Investigation of Fracture Initiation by Ductile Failure Mechanisms in a 4340 Steel", *U.S. National Congress of Applied Mechanics,* University of Arizona, May, 1990.

D. BOOKS (AND SECTIONS THEREOF)

Edited the following volumes

1. Co-editor of the Proceedings of the IUTAM Symposium on Non-linear Fracture Mechanics, Caltech, March 1988. Special issue of the *International Journal of Fracture* devoted to Non-linear Fracture Mechanics, 1990.
2. Co-editor of the Proceedings of the Workshop on "Three-Dimensional Fracture Processes", (ASME, AMD - Vol. 91.) Joint ASME/SES meeting, Berkeley, California, June 1988.
3. Guest Editor of the Special Issue of the *International Journal of Optics and Lasers in Engineering*, devoted to the "Optical Method of Caustics", Vols. 13, 14, 1991.

LIST OF AWARDS (ENCLOSURE (3))

Name of Person Receiving Award	Recipients Institution	Name of Award	Sponsor of Award
Prof. Ares J. Rosakis Prof. Alan T. Zehnder Prof. R. Narasimhan	Caltech Cornell IIT Bombay	Rudolf Kingslake Medal and Prize	International Society of Optical Engineering (SPIE)

The award was presented to the above individuals in recognition of the most noteworthy original paper to appear in the *Journal of Optical Engineering* (SPIE's offical journal).

The paper was entitled, "Caustics by Reflection and their Application to Elastic-Plastic and Dynamic Fracture Mechanics". Drs. Zehnder and Narasimhan were supported by the current ONR contract when this work was completed.

PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS REPORT

(ENCLOSURE (4))

(Number Only)

Papers submitted to Refereed Journals (and not yet published)	2
Papers Published in Refereed Journals	22
Papers Published in Non-Refereed Journals	0
Technical Reports Published	20
Books (and sections thereof) submitted for Publication	0
Books (and sections thereof) Published	3
Patents Filed	0
Patents Granted	0
Invited Presentations at Topical or Scientific/Technical Society Conferences	8
Contributed Presentatiosn at Topical or Scientific/Technical Society Conferences	17
Honors/Awards/Prizes	1
Number of Graduate Students	4
Number of Post Docs	4